MEMORANDUM

Wyckoff Sheet Pile Wall – Thickness Testing, 2017

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This memorandum summarizes thickness measurements of the sheet pile wall at the Wyckoff facility on Bainbridge Island, Washington. The field tests were performed on May 24, 2017.

Background

A sheet pile wall was installed around the outer, shoreline perimeter of the Wyckoff remediation site. Construction of the sheet pile wall was completed in February 2001. The wall is approximately 1,870 feet long and extends to a depth approximately 20 to 90 feet below grade. The general arrangement of the sheet pile wall is shown in Figure 1.

Figure 1. General arrangement of sheet pile wall around the Wyckoff Facility.

The sheet pile wall was constructed using British Steel Z '5' section sheet piling—also referred to as Frodingham #5 sheet pile. Figure 2 shows a typical individual pile with interlocking joints. Dimensions of the piles, include thickness, are also included in Figure 2. The sheet pile wall consists of 674 piles, with two interlocking joints per pile.

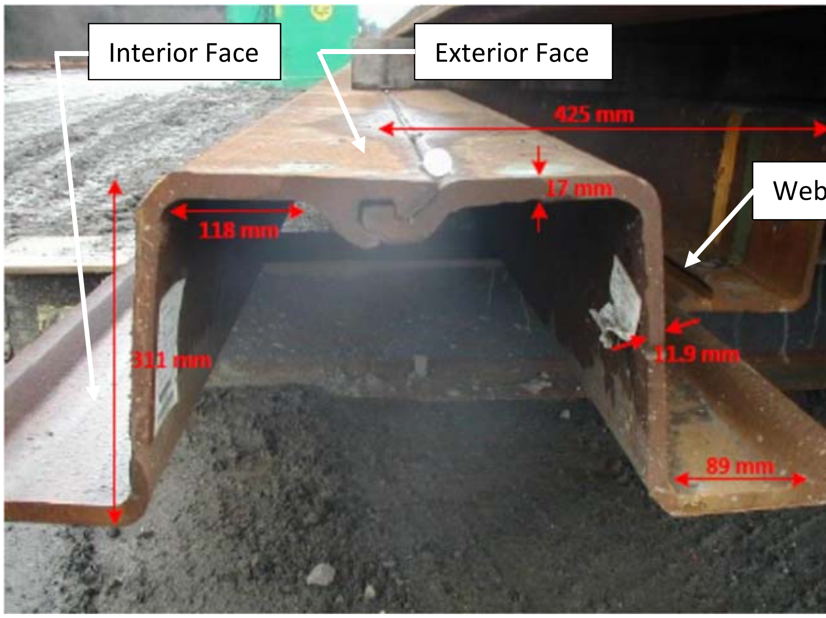


Figure 2. Dimensions of steel piling.

For the purposes of this work, the faces of the Z-piles that were tested are defined as shown in Figure 2. The original thickness values for each face are summarized in Table 1.

TABLE 1
Sheet Pile – Original Wall Thickness Values

Face	Original Thickness (mm)	Original Thickness (mils)
Exterior Face	17	669
Web	11.9	468
Interior Face	17	669

Summary and Results of Testing

Field tests included general observations, measurement of sheet pile thickness, and measurement of distance between the top of the wall and the mud line (water side) and fill (soil side). These tests were performed at seven locations distributed around the perimeter of the sheet pile wall (see Figure A1, included at the end of this memorandum). The thickness of the piling was measured at one or a combination of 5 vertical spots at each test location. Vertical spot definitions, dimensions, and general description of the piling condition (as found) are summarized in Table 2.

TABLE 2
Pile Test Locations, Vertical

Spot Definition	Typical Distance from Top of Wall to Test Spot (ft)	General Condition, As Found
"Atmospheric"	3	Surface rust
"Splash"	6	Heavy corrosion products (up to 1-inch thick); orange stains on north side
"Tidal"	9.5 – 11.5	Marine growth; tightly adhered corrosion products, moderately thick
"Submerged"	11 – 13.5	No corrosion products or marine growth
"Mud"	12 – 14.5	Thin, tightly adhered corrosion product

General Appearance

The general appearance of the sheet pile wall was similar to that observed in 2013, with one significant difference. The interlocks along the interior faces of the piles have significant loss of metal at the mud line (see adjacent photograph). The deterioration is very localized at the interior face interlock; no significant deterioration was noted on the pile surfaces adjacent to the interlock or on the interlock surfaces located along the exterior faces of the piles. The deterioration of interlocks appears to be most significant along the east wall. Although no obvious cause of the deterioration was identified, it is possible that the metal loss in this area is being caused by stones and gravels that are pushed against the joint by wave actions.

Corrosion of interlocks at mudline.

The condition of the piling zones at several test locations is shown in the photographs included at the end of this memorandum.

Wall Height Measurements

The distance from the top of the wall to the mud line (seaside) and the top of the wall to the fill (landside) were checked with a measuring tape. These dimensions are shown in table 3, and compared to dimensions measured in 2013. The change in soil elevation on the water side of the pile showed a variation of minus 2 to plus 11 inches, indicating some movement of the beach soils has occurred. A soil elevation variation of minus 4 to plus 1 was noted on the land side of the wall. There was no apparent reason for the small increase in soil elevation on the land side.

TABLE 3
Dimension from Top of Wall

Test Location	Top of Wall to Mud, Seaside			Top of Wall to Fill, Landside		
	2013	2017	Variation	2013	2017	Variation
1	13'-7"	13’-10”	+3”	2'-10"	2’-10”	0”
2	14'-6"	14’-4”	-2”	3'-0"	2’-9”	-3”
3	13'-7"	14’-6”	+11”	3'-2"	3’-3”	+1”
4	13'-0"	13’-8”	+8”	2’-11"	3’-0”	+1”
5	11'-2"	11’-4”	+2”	2’-11"	2’-7”	-4”
6	13’-0”	12’-8”	-2”	3'-2"	3’-3”	+1”
7	12'-10"	No Test	N/A	3'-3"	No Test	N/A
8	12'-10"	12’’-6”	+6”	2’-11”	2’-11”	0”
9	12'-9"	No Test	N/A	2'-3"	No Test	N/A

Metal Thickness Testing

The thickness of the steel piles was measured using ultrasonic test methods. Sheet pile thickness tests were made by mechanically removing rust deposits and grinding small spots to achieve the smooth, clean surface required for the test. Thickness test were made with a Krautkramer Model DM4E ultrasonic thickness gauge. The gauge was field calibrated before and during testing. The results of the thickness measurements, including the 2013 data, are summarized in Table A1 (attached).

The average measured thickness values from the 2017 testing are compared to the original nominal thickness, and the resulting decrease in thickness are summarized in Table 4. Table 4 includes average measured thickness from the 2013 testing and resulting decreases in thickness when compared to the original.

TABLE 4

Summary of Thickness Measurements and Metal Loss

	Initial	2017 Measured (Average)	Percent Reduction (2017)	2013 Measured (Average)	Percent Reduction (2013)
			Thickness (mils)		
Atmospheric Zone					
Test Point[1] A	669	616	8%	660	1%
B	468	447	4%	454	3%
C	669	639	4%	636	5%
D	669	655	2%	649	3%
E	468	432	8%	346	n/a
F	669	611	9%	620	7%
Average Loss-->			***6%***		***4%***
Splash Zone					
Test Point A	669	560	16%	599	11%
B	468	345	26%	386	18%
C	669	577	14%	592	12%
D	669	562	16%	602	10%
E	468	356	24%	362	23%
F	669	592	12%	639	5%[3]
Average Loss-->			***18%***		***13%***
Tidal Zone					
Test Point A	669	632	6%	656	2%
B	468	427	9%	428	9%
C	669	661	1%	673	-1%
D	669	640	4%	652	2%
E	468	429	8%	443	5%
F	669	640	4%	651	3%
Average Loss-->			***5%***		***3%***
Submerged					
Test Point A	669	669	0%		
B	468	446	5%	478	-2%[4]
C	669	670	0%	682	-2%[4]
D	669	656	2%	667	0%
E	468	454	3%	459	2%
F	669	664	1%		
Average Loss-->			***2%***		***0%***
1' Below Mud Line					
Test Point A					
B					
C	669	642	4%	675	-1%[4]
D	669	660	1%	674	-1%[4]
E					
F					
Average Loss-->			***3%***		***-1%[4]***

[1]See figure in Table A1 (attached) for test point locations on the piles.
[2]High percent reduction based on one data set at one pile; not included.
[3]Based on one spot measurement at one location.
[4]Negative percentage metal loss may be due to allowable dimension tolerances.

Conclusions

Table 4 shows that metal loss from corrosion is continuing to occur. The average of thickness values in 2017 are consistently lower than the average thickness values measured in 2013.

The specific reduction of metal wall thickness due to corrosion for each “zone” are described below. Estimated corrosion rates are based on the reduction in thickness measured in 2017 compared to the original sheet pile thickness values - 0.669-inch (669 mils) for interior and exterior faces, 0.448-inch (448 mils) for webs, and an exposure period of 16 years.

“Atmospheric” Zone

Surface corrosion and shallow pitting was observed on the seaside face of the sheet pile wall in the “atmospheric” zone. However, corrosion is occurring on the landside of the wall at the soil/air interface (thick corrosion products on the steel piling are visible at the soil surface on the landside of the structure). This corrosion is due to chloride and oxygen at the soil-to-air interface on the landside. It is assumed that chlorides are concentrating in the soil on the landside due to seawater splash. The test measurements show reduction in wall thickness in this zone.

The rate of general metal loss in “atmospheric” zone, based on 2017 data, ranged from 0.9 to 5.3 mils per year with an average of 2.9 mils per year. The relatively high and variable corrosion rate for this zone appears to be due landside corrosion activity.

“Splash” Zone

Heavy corrosion products are present in this zone. General metal loss and corrosion pitting is occurring. The effect of corrosion is more significant on the north side of the wall; the corrosion products have a different appearance in this area and deeper pits were observed.

The rate of general metal loss in the “splash” zone, based on 2017 data, ranged from 5.7 to 16.8 mils per year, with an average of 10.8 mils per year. Pitting rates in this zone (based on 2013 tests) are estimated to be 12.5 mils per year.

“Tidal” Zone

The “tidal” zone area exhibited more marine growth than the other zones. Moderately thick, tightly adhered corrosion products were found. Some pitting is occurring, but to a lesser extent than that observed in the “splash” zone.

The rate of general metal loss in the “tidal” zone, based on 2017 data, ranged from 0.5 to 8.0 mils per year with an average of 4.8 mils per year.

“Submerged” Zone

Very little corrosion or pitting was observed in the “submerged zone (12 to 18-inches above the mud line, and below the marine growth associated with the “tidal zone). Very thin surface rust was observed in this area.

The rate of general metal loss in the “submerged” zone, based on 2017 data, ranged from 0 to 1.4 mils per year with an average of 0.5 mils per year.

Although general corrosion rate of the flat surfaces of the piling was low in this zone, rapid deterioration was observed on the interlocks along the interior face of the piles. One interlock was found to have a remaining wall thickness of only 0.10”. See Photograph 11, attached.

Reference drawings show the interlock thickness to be approximately the same thickness as the flat surfaces of the interior face of the sheet. Therefore, the corrosion rate of the interlock is estimated to be as high as 35 mils per year ([669 mils original-105 mils remaining/16 years]). At this rate, penetration of the interlocks could begin to occur within the next three to four years. Due to variations in corrosion noted on the interlocks along the sheet pile wall, there is possibly that some penetrations of the interlocks could occur within a year.

The cause of this rapid corrosion rate was not identified. Metal deterioration rates in this range are usually associated with bacteria, stray current, or abrasion. Rapid corrosion by stray current and bacteria are usually distributed along the entire surface and are not localized as observed on this wall. It appears that a more probable source of deterioration is abrasion due to concentrated wave effects (with suspended rocks and beach sand) at the interior pile interlock. There are some indications that deterioration of the interlocks was starting in 2013 (based on a review of previous photographs), but the deterioration was not nearly advanced as that observed in 2017. One possible reason for an increase in abrasion at this location is an increase in wave energy.

"Mud" Zone

The piling 12-inches below the mud level on the seaside surface of the wall exhibited some minor corrosion pitting in places. A thin, tightly adhered layer of corrosion products were present. Although there is red rust staining below the mud line, the corrosion products appear to be more protective than those in the splash and tidal zones (most likely due to lower oxygen availability in the soil). Corrosion rates are relatively low in this area, compared to those measured in the splash and tidal zones.

The rate of general metal loss in the "mud" zone, based on 2017 data, is 0.6 to 1.7 mils per year with an average of 1.1 mils per year.

ATTACHMENTS

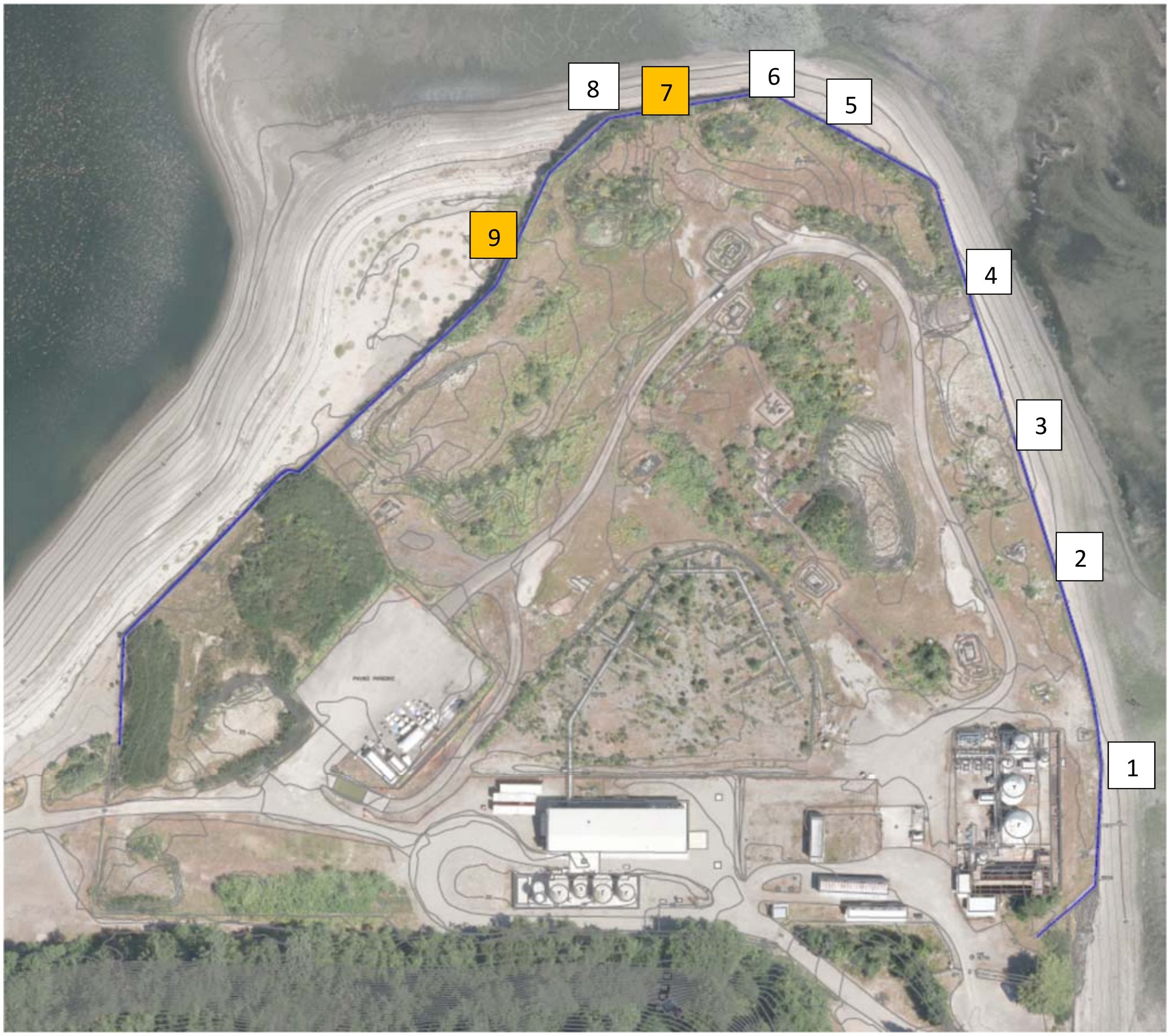
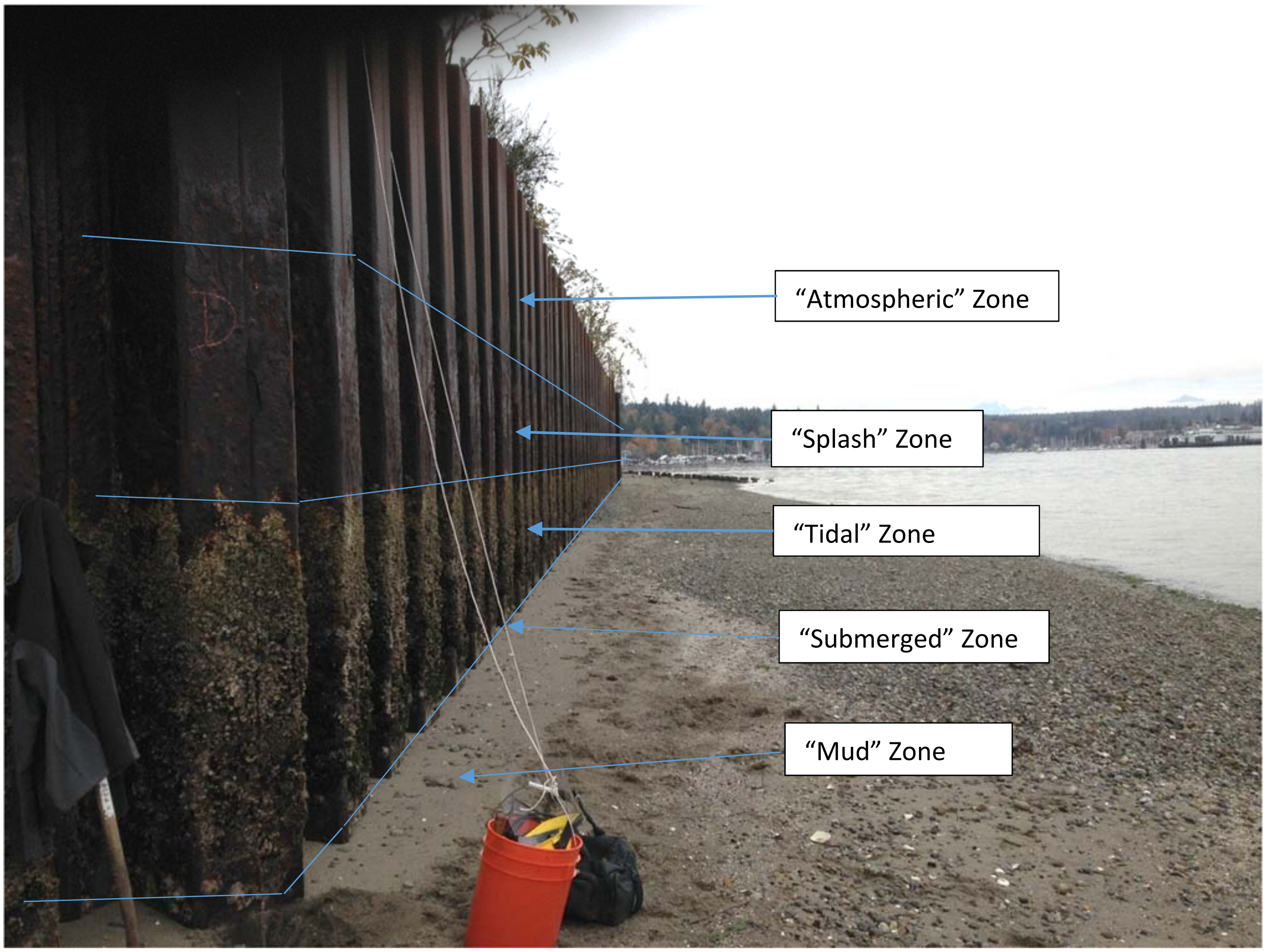


Figure A1. Sheet Piling Test Locations. No tests at highlighted locations.



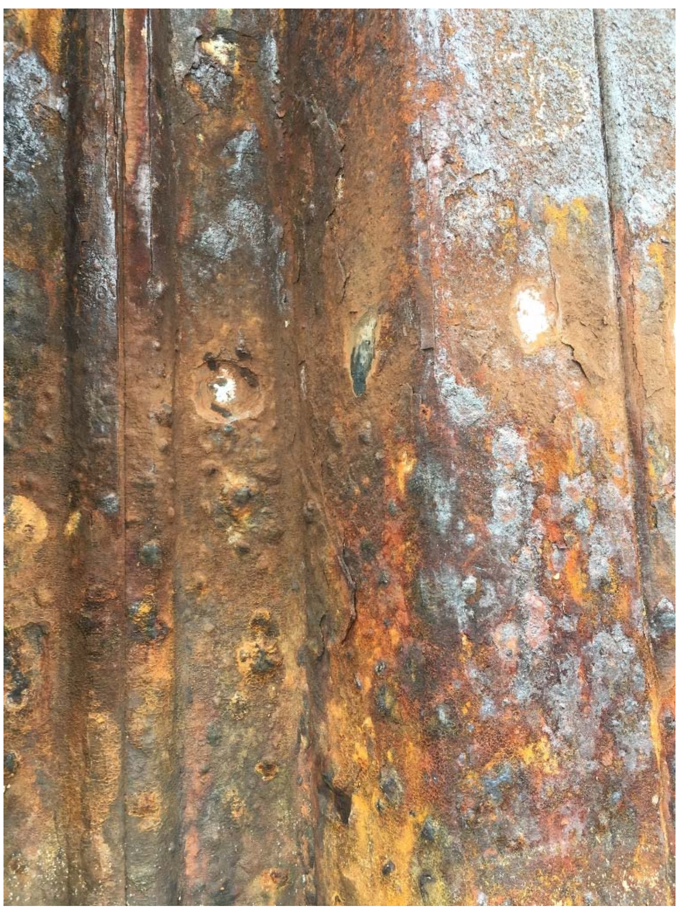
Photograph 1. General condition of the sheet pile wall in 2013, Wyckoff (Bainbridge Island), with exposure "zones" shown. North face.

Photograph 2. General condition of the sheet pile wall (north face) in 2017,

Photograph 3. General condition of sheet piling in 2013, northwest side of facility.

Photograph 4. General condition of sheet piling in 2013, northwest side of facility.

Photograph 5. Photograph illustrates the thickness and color of corrosion products in the "splash" zone (2013). Note the bright orange appearance on the surface, indicating active corrosion.



Photograph 6. Appearance of the steel in the splash zone in 2017 was very similar to that observed in 2013.

Photograph 7. Condition of sheet pile wall in the tidal zone (2017).

Photograph 8. <-- The white arrow shows the assumed location where corrosion products on the east wall were damaged by a thrown rock. Concern was voiced that the rock had penetrated the metal surface and soil fill behind the wall could be observed through a hole.

Photograph 9. → Close-up of corrosion product damaged by thrown rock. Although there appears to be soil-colored material in the damaged area, an intact metal surface is visible (dark gray material at center).

Photograph 10. <-- Corrosion product was removed from the surface. Pitting (localized corrosion) was observed, but it did not penetrate the sheet pile.

Photograph 11. <-- Significant deterioration of the interlock was observed at the "mud" line. Note that the surface is free of marine growth, and the rocky condition of the beach soil. The clean surface and localized corrosion of the interlock may be due to a combination of abrasion (erosion) and corrosion. Also note the metal thickness values written on the sheet pile (651 mils above the affected zone vs 105 mils at the affected area).

Photograph 12. → Some metal loss of the interlock due to corrosion is occurring below the "mud" line, but it is significantly less that the surface immediately above the "mud" line.

Photograph 13. <-- General condition of sheet pile below the “mud” line.   The surfaces below the soil line are covered with relatively thick, tightly adhering corrosion products.

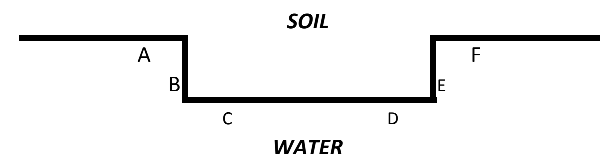
Photograph 14. → The metal surface below the soil line was in relatively good condition when the corrosion products were removed. The bright orange just above the mud line appears to be surface rust and may be associated with steel that is being abraded (exposing fresh steel). However, no significant metal loss was measured in either of these locations, and was less than the metal loss in the atmospheric, splash, and tidal zones.

TABLE A1

Wyckoff

Sheet Pile Thickness Measurements

2017



Test Point Locator

Location --->	1(A)			2(B)			3(G)			4(C)			5(H)			6(D)			8(E)			Original Thickness Mils	Percent Reduction 2017
										Thickness (mils)													
Year-->	2017	2013	Δ	2017	2013	Δ	2017	2013	Δ	2017	2013	Δ	2017	2013	Δ	2017	2013	Δ	2017	2013	Δ		
Atmospheric		3'-0"			3'-0"			3'-0"			3'-0"			3'-0"			3'-0"			3'-0"			
A	439			593			620			667			659	660	-1	670			663			669	8%
B	410			425				448		485			450	459	-9	470			442			468	4%
C	672			548			637	636	1				699									669	4%
D	617			656			632	646	-14	651			654	651	3	681			694			669	2%
E	405			605			348	350	-2	453			331	341	-10	446			436			468	8%
F	496						617			625			578	620	-42	707			645			669	9%
Average Loss-->									*-5*						*-12*								6%
Splash		6'-0"			6'-0"			6'-0"			6'-0"			6'-0"			6'-0"			6'-0"			
A	536			565	564	1	543	567	-24	575	604	-29		619			609		580	629	-49	669	16%
B	300			332			326	356	-30		367		363	393	-30	356	390	-34	393	422	-29	468	26%
C	762			486	545	-59	564	589	-25		679			585			577		497	577	-80	669	14%
D		650		492	548	-56	544	590	-46	659	671	-12	553	591	-38		577		563	590	-27	669	16%
E	332			367				285		375			352	402	-50	341	374	-33	366	385	-19	468	24%
F	585			642			545	584	-39	580			594	693	-99	604			593			669	12%
Average Loss-->						*-38*			*-33*			*-21*			*-54*			*-34*			*-41*		18%
Tidal		12'-0"			11'-6"			11'-6"			10'-7"			11'-4"			10'-6"			9'-8"			
A	639			641				643		663			592	669	-77	623			633			669	6%
B	443			426			458			450			421	428	-7	365			426			468	9%
C		670		661	665	-4		653			672			790			624			634		669	1%
D	623	625	-2	668	670	-2	653	656	-3	657	669	-12	597	665	-68		640		640	641	-1	669	4%
E	433			409			456			442			403	443	-40	438			423			468	8%
F	658			658				641		645			611	660	-49	661			608			669	4%
Average Loss-->			*-2*			*-3*			*-3*			*-12*			*-48*						*-1*		5%
Mud		13'-10"			14'-4"			14'-6"			13'-8"			12'-3"			12'-8"			12'-6"			
A	661			672						675												669	0%
B	445			452				478		442												468	5%
C		668		670	674	-4		743			661						662					669	0%
D	652	659	-7	669	686	-17		650		647	689	-42					650					669	2%
E	464			470				459		429												468	3%
F	655			665						672												669	1%
Average Loss-->			*-7*			*-11*						*-42*											2%
Mud-1'		14'-10"			15'-4"			15'-6"			14'-8"			13'-3"			13'-8"			13'-6"			
A																							
B																							
C	630	668	-38				638			630	676	-46	665	662	3		732			639		669	4%
D	659				676		650			660	685	-25	660	657	3	670	709	-39		645		669	1%
E																							
F																							
Average Loss-->			*-38*									*-36*						*-39*					3%
Interlock																							
16" above mud				651			631						646										
at mud	431			105									448										
6" below mud	591						551						617										